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Can decontamination and reuse of N95 respirators during COVID-19 pandemic provide energy, environmental, and economic benefits?

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ABSTRACT

The widespread COVID-19 pandemic led to a shortage in the supply of N95 respirators in the United States until May 2021. In this study, we address the energy, environmental, and economic benefits of the decontamination-and-reuse of the N95 masks. Two popular decontamination methods, including dry heat and vapor hydrogen peroxide (VHP), are investigated in this study for their effective pathogen inactivation and favorable performance in preserving filtration efficiency and structural integrity of respirators. Two multiple reuse cases, under which the N95 masks are disinfected and used five times with the dry heat method and 20 times using the VHP method, are considered and compared with a single-use case. Compared to the single-use case, the dry heat-based multiple-use case reduces carbon footprint by 50% and cumulative energy demand (CED) by 17%, while the VHP-based case decreases carbon footprint by 67% and CED by 58%. The dry-heat-based and VHP-based multiple reuse cases also present environmental benefits in most of the other impact categories, primarily due to substituting new N95 respirators with decontaminated ones. Decontaminating and reusing respirators costs 77% and 89% less than the case of single-use and disposal. The sensitivity analysis results show that the geographical variation in the power grid and the times of respirator use are the most influential factors for carbon footprint and CED, respectively. The result also reaffirms the energy, environmental, and economic favorability of the decontamination and reuse of N95 respirators.

1. Introduction

1.1. The critical role of used N95 respirator decontamination

Reusing N95 respirators is a crisis capacity strategy to implement when other engineering and administrative control measures are not able to meet the current or anticipated demand for filtering facepiece respirators (FFRs) [1]. This strategy had been implemented in the United States (U.S.) until May 2021 [2], and also in other regions of the world, such as the European Union [3] and Brazil [4], under acute supply shortages of FFRs. N95 respirators protect healthcare workers during high-risk, aerosol-generating procedures [5]. Conventionally, used N95 respirators are categorized as regulated medical waste (RMW) and are processed through the hospital, medical, and infectious waste incinerators (HMIWI). However, since early 2020, the COVID-19 pandemic has strained the health care system with remarkably high demand for N95 respirators [6]. According to a survey conducted in 2020, one-third of over 20,000 U.S. nurses reported a shortage in FFRs, and 68% of them were required to reuse N95 masks in their workplaces [7]. Moreover, more than half of the nurses reused N95 respirators for at least five days [7]. Recently, India is experiencing raging outbreaks of COVID-19, reporting over 300,000 daily confirmed cases [8]. This COVID-19 surge may make the severe shortage of FFR in India even worse [9]. Thus, decontamination and reuse of FFRs are urgently needed to alleviate the shortage of new FFRs.

The U.S. Food and Drug Administration (FDA) issued emergency use authorizations for N95 respirators decontamination systems in 2020 in response to the supply shortage [10]. For example, Battelle was awarded a $415 million-dollar contract for 60 Critical Care Decontamination Systems (CCDS), each of which can decontaminate up to 80,000 N95 masks [11]. With decontamination systems increasing the availability of N95 masks, reductions in deaths and infections can be achieved, and pressure on healthcare systems is expected to be relieved to some extent [12]. Promoting the FFR decontamination and reuse under limited supply might support public health but may also require less energy, reduce environmental harms, and relieve financial burdens on

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healthcare facilities by reducing the FFR demand. However, the energy, environmental and economic benefits of decontaminating N95 respirators vary according to different technology options and the choices of operational parameters. Therefore, a systematic evaluation of the energy, environmental and economic performances for the FFR decontamination methods is urgently needed to identify the hotspots for further improvement of decontamination practices.

1.2. Literature review

Previous studies on FFR decontamination investigated the impact of different decontamination methods [13] on the filtration performance of various FFR models [14]. Recent studies mainly focused on the maximum number of decontamination cycles under different conditions, including treatment time [15], temperature [16], and humidity [17], before passing the threshold of filtration efficiency and structural integrity. Disinfected N95 respirators can maintain high filtration efficiency and structural integrity that effectively protect health care personnel, patients, and susceptible individuals [16]. Potential decontamination methods include dry heat [18], moist heat [16], ultraviolet irradiation [19], ethylene oxide [20], ethanol [15], vaporized hydrogen peroxide (VHP) [21], and microwave-generated steam (MGS) [22]. Dry heat and moist heat methods are accessible and easy to implement. Most studies find that low temperature (70-85℃) [15] and intermediate humidity [17] are optimal for maintaining structural integrity under heat treatments lasting 30–60 min [15], although filtration efficiency can be preserved under temperatures up to 100℃ [18]. Notably, since dry heat is not effective against all pathogens [17], the respirators should be stored in a breathable paper bag for at least five days between each use to allow the pathogens to vanish [1]. VHP decontamination is more effective in pathogen inactivation for the heat-sensitive respirators [23] and less damaging to filtration efficiency and structural integrity [15]. However, the concentrations of VHP and pathogens, type of VHP decontamination systems, and types of commercially available FFRs vary extensively among existing studies [19]. MGS can also effectively decontaminate FFRs [24], although it was reported to damage the respirators' components [22] and structure [14]. Ultraviolet is a highly effective method to sterilize most pathogens on FFRs with doses exceeding 1 J/cm^2, as confirmed by many studies on a variety of examined pathogens [25], types of FFRs [25], doses of ultraviolet light [26], and ultraviolet-generating systems [27]. Notably, few studies evaluate the effectiveness of sterilizing used respirators on SARS-CoV-2 contamination. The results of Ozog et al. [27] and Fischer et al. [15] suggest that a dose exceeding 1.5 J/cm^2 may be required to kill SARS-CoV-2 effectively, and additional disinfection may be needed for the straps. Moreover, the effectiveness of ultraviolet varies considerably for different types of FFRs [19], and the position and orientation of N95 masks must be carefully arranged to avoid shadowing [28] and allow complete exposure to ultraviolet light [27]. The efficacy and safety of the ethylene oxide method on disinfecting used respirators are uncertain and controversial due to the limited studies so far [19]. In particular, insufficient aeration of ethylene oxide may cause severe injury to human health [28]. Ethanol decontamination is found to destroy respirators' filtration efficiency after only the first decontamination cycle [15]. In addition, 3 M, a leading manufacturer of FFR, discourages ethylene oxide, ethanol, and microwave on all their FFR products. Therefore, dry heat and VHP are considered in this work due to their data availability, high efficiency in pathogen inactivation, wide availability, relatively simple operations, and reliability in preserving filtration efficiency and structural integrity of N95 masks, with abundant evidence from existing literature as discussed above.

1.3. Knowledge gaps and novelties

Reusing respirators is one of the best available solutions to protect the healthcare workers and alleviate the immense pressure on the healthcare systems under the pandemic-induced shortage of critical medical supplies. Dry heat and VHP decontamination methods are examined in this study owing to their capability of preserving filtration efficiency and structural integrity of N95 masks, the effectiveness of pathogen inactivation, and good accessibility, as stated in §1.2. Both decontamination methods have the potential of increasing the number of donning to at least five times for FFRs before discarding and incinerating them. Decontaminating and reusing respirators could potentially provide environmental benefits from the avoided production of new FFRs. On the other hand, the economic viability of decontaminating FFRs is unclear but vital to the selection of decontamination systems for the healthcare facilities and the amount of financial support from the government. Therefore, it is important to investigate the environmental and economic benefits of decontaminating and reusing N95 respirators compared to their one-time use approach. However, no existing literature examines the environmental and economic performances of FFR decontamination, which remains a critical knowledge gap. To fill this knowledge gap, we conduct a comparative life cycle assessment (LCA) and techno-economic analysis (TEA) to evaluate the benefits of reusing the N95 masks through the dry heat and VHP decontamination methods before final treatment by incineration, in comparison to the case of single-use and disposal of FFRs.

Several research challenges should be addressed in this work. The first challenge is to systematically evaluate the energy, environmental, and economic benefits of reusing FFRs via different decontamination methods relative to the single use of FFRs. The second challenge is to select a suitable functional unit to fairly compare across different FFR use cases. The third challenge is to investigate the impacts of the uncertainty in the life cycle inventory (LCI) and economic data, which could have pronounced impacts on the LCA and TEA results.

This article systematically evaluates and compares the carbon footprint, cumulative energy demand (CED), and environmental impacts across a comprehensive list of ReCiPe midpoint and endpoint indicators for two decontamination-based respirator multi-use cases and the single-use case following the LCA methodology. All these cases have incineration as the final stage for waste management, and they differ in terms of the reuse and decontamination stages. Details of these cases are given in §2. Moreover, we perform TEA to quantify the economic benefits of decontamination and reuse of waste respirators. The environmental and economic hotspots are identified throughout the life cycle of used FFRs. Owing to the uncertainty in the considered input parameters, we conduct a sensitivity analysis to examine the impact of these uncertainties on the carbon footprint, CED, and economic results. We also assess the impact of the geographic variation in the power grid on climate change and energy use.

Key contributions of this work are summarized as follows:

- The first LCA and TEA results on energy, environmental, and economic benefits of reusing N95 respirators through two most popular and reliable decontamination methods, namely dry heat and VHP, in comparison to the one-time use case;
- The identification of environmental and economic hotspots that addresses the most influential contributors for FFR reuse and decontamination;
- Comprehensive spatial and sensitivity analyses to determine the most sensitive parameters based on the proposed LCA and TEA models to further improve decontamination practices.

The remainder of this paper is organized as follows. We describe the decontamination processes and the proposed LCA and TEA methodologies in §2. The LCA and TEA results are presented in §3 to assess the environmental and economic benefits of the dry heat and VHP decontamination methods, followed by sensitivity analyses on the economic and environmental parameters. The conclusions are given in §4.

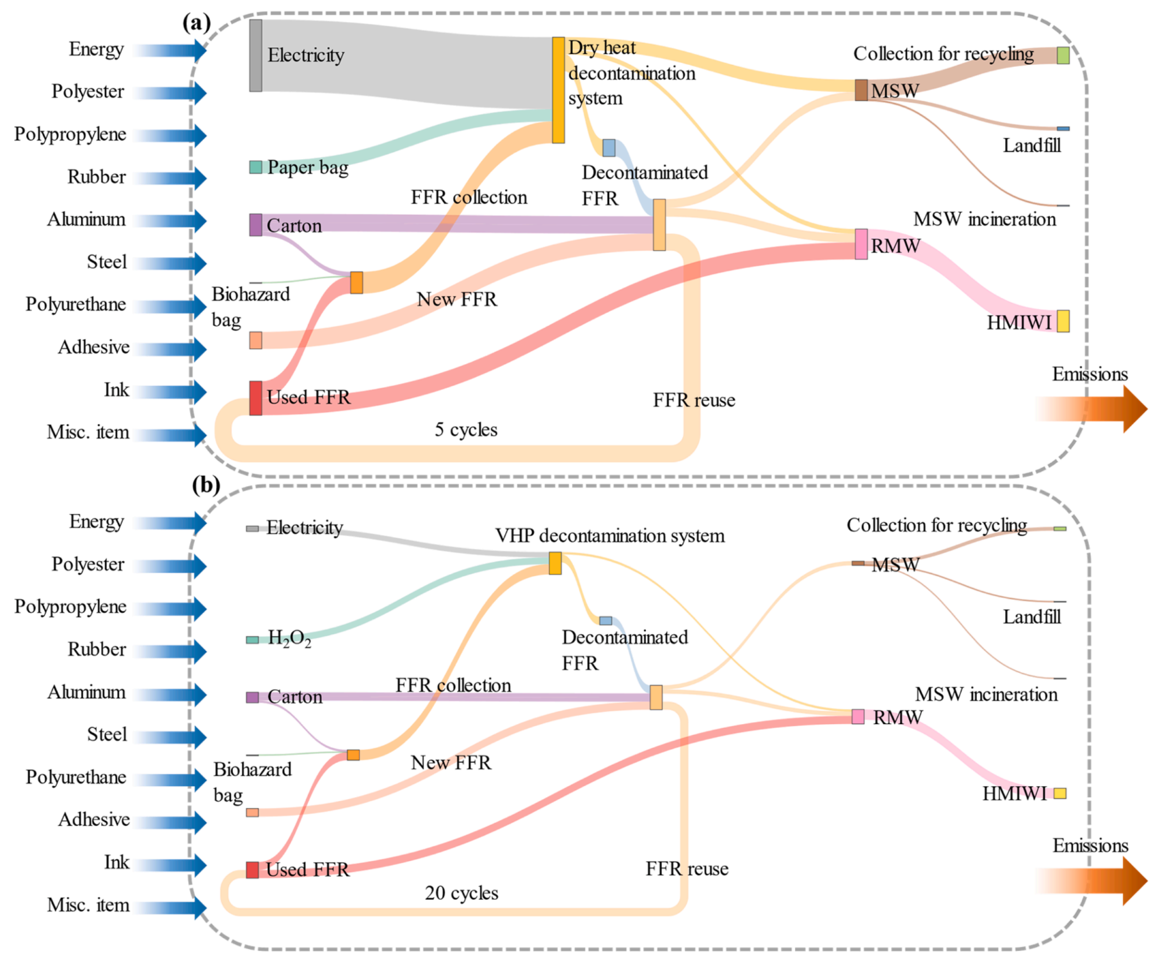

Fig. 1. System boundary of the "cradle-to-grave" LCA for the decontamination-and-reuse of FFRs. HMIWI denotes the hospital, medical, and infectious waste incinerators.

Table 1
Detailed composition of a typical N95 mask [34].

Component	Amount (g)
Polyester	2.55
Polypropylene	5.67
Rubber	1.70
Aluminum strip	0.57
Steel	0.23
Polyurethane foam	0.23
Adhesive	0.11
Ink	0.01
Total	11.06

2. Methods

In this work, we performed a holistic LCA to systematically analyze and compare the energy use and full-spectrum environmental implications of reusing N95 respirators multiple times via two decontamination-based technology, in comparison with the one-time use case. The three cases are described as follows:

- **Dry heat-based multiple reuse case:** this case employs the dry heat decontamination technology to allow using/reusing the FFRs 5 times before final disposal via incineration.
- **VHP-based multiple reuse case:** this case considers 20 times of using/reusing FFRs with the help of the VHP decontamination technology, followed by incineration of FFRs due to attaining the maximum numbers of reuse.
- **Single-use case:** in this case, the FFRs are incinerated after their one-time use.

The LCA methodology is conducted in four phases: goal and scope definition, LCI, life cycle impact assessment (LCIA), and interpretation. The details of the four phases are presented in the following subsections. Moreover, techno-economic analysis is conducted to evaluate the economic benefit of the decontamination-and-reuse approaches.

2.1. Process description

The technology pathways of the three cases are shown in Fig. 1. First, after each use, used FFRs are labeled and collected in two layers of plastic biohazard bags. In the single-use case, the closed biohazard bags are placed in a reusable rigid container and transported directly to the HMIWI. The closed collection bags are placed into a carton for the dry-heat-based and VHP-based multiple reuse cases. The carton is ready for shipping to the decontamination facilities after labeling and taping. Once the decontamination facilities receive the used FFRs, the respirators are unpacked, inventoried, and hung on racks before being disinfected. And the carton and biohazard bags are sent to the HMIWI for disposal due to their containment of potentially infectious wastes. After the decontamination and aeration, N95 masks are taken down, packed into cartons, and delivered back to the healthcare facility.

In this study, we adopt the Battelle CCDS with High-Efficiency Particulate Arrestance (HEPA) filters as a representative VHP method because it was approved by FDA and deployed at large scales across the U.S. Each Battelle CCDS consists of four decontamination containers,

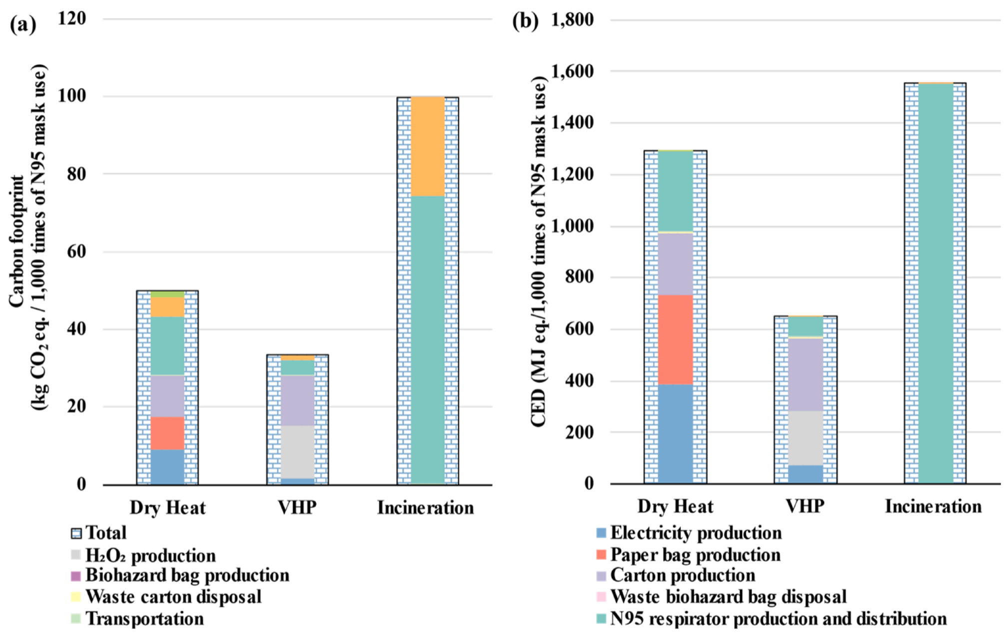

Fig. 2. Comparison of (a) carbon footprint and (b) CED for the dry-heat-based and VHP-based multiple reuse cases and the single-use case.

which treat up to 10,000 used FFRs per cycle [29]. The capacity of Battelle CCDS is 80,000 respirators per day. Each cycle consists of four phases: a 10-minute conditioning phase, a 20-minute gassing phase, a 150-minute dwell phase, and a 300-minute aeration phase [23]. The VHP injection rate is 2 g per minute for the gassing phase and 0.5 g per minute for the dwell phase in the laboratory chamber (0.31 m^3) [23]. Hence, the average VHP concentration is estimated as 371 ppm in each decontamination container. Based on the size of the four chambers, 477.23 kg VHP is consumed for each cycle. After aeration, five chemical indicators are dispersed throughout the system to indicate the successful reduction of VHP to < 1 ppm before the FFRs are released for packing [30]. Twenty decontamination cycles can be applied to a single N95 respirator [30]. In addition, 75 kWh of electricity is consumed per cycle [29].

For the dry heat decontamination system, a commercial sterilizer with HEPA filters is used as a representative [31]. This commercial model is chosen due to its accessible economic and operational parameters. Each used FFR is sealed in an autoclavable paper bag with heat indicator tape and placed in the sterilizer. Pathogen inactivation by dry heat is highly sensitive to temperature and time [32]. Therefore, for each decontamination cycle, we follow the guidance from the FFR manufacturer and consider treating 1,000 contaminated N95 masks at 70℃ for 60 min [26]. The dry heat decontamination system is capable of treating 36,000 FFRs per day. Each N95 respirator is expected to undergo four decontamination cycles [1]. In addition, 48 kWh of electricity is consumed per cycle.

2.2. Goal and scope definition

The scope of this "cradle-to-grave" LCA focuses on treating used N95 respirators. The system starts from the acquisition of raw materials (i.e., the components of FFRs and auxiliary materials) and ends at the disposal of the FFRs and wastes after multiple uses. The decontamination methods aim to extend the number of FFR uses. Therefore, the functional unit is defined as the 1,000 times of uses/reuses of N95 respirators, following the existing literature [33]. The system boundary includes five life cycle stages: N95 respirator production and distribution, production of auxiliary materials, respirator storage and transportation, respirator decontamination, and reuse and disposal. Detailed LCI for each life cycle stage is described in §2.3.

2.3. Life cycle inventory

The materials and energy inputs and outputs associated with the 1,000 times of FFR uses are compiled using data estimated from technical reports, governmental documents, and product specification reports (Table A1, in Appendix).

2.3.1. N95 Respirator production and distribution

N95 masks are produced from several components, including the filter media made from non-woven polypropylene and polyester, head straps made from synthetic rubber, aluminum nose clip, polyurethane nose foam, steel wires, adhesive, and ink, as presented in Table 1 [34]. Among these components, the nose clip is manufactured from aluminum ingots through sheet rolling and wire drawing [35]. Similarly, the steel wires are manufactured from cast ingots through hot rolling, sheet rolling, and wire drawing. The final manufacturing step involves electricity consumption of 0.8 kWh per 1,000 masks associated with mask body forming, earloop cutting, and ultrasonic welding [36]. It is worth mentioning that the electrostatic charge step for improving the filtration efficiency of respirators is excluded with no reliable data on its electricity consumption [37]. Missing this manufacturing step may lead to conservative estimates on the environmental impacts of N95 mask production. Each piece of the N95 mask weighs 11 g approximately [38]. Subsequently, 20 pieces of the N95 masks are packed per box [34]. Moreover, 40 boxes are shipped 1931 km in a carton from the manufacturer to the geographic center of New York State (NYS) [36].

2.3.2. Production of auxiliary materials

Sterilization of used respirators involves the input of auxiliary materials to support other life cycle stages. In particular, proper collection, packaging, and storage of the used FFRs are required before transportation to prevent the leakage of these medical wastes and avoid viral transmission, according to the Centers for Disease Control and Prevention (CDC) of the U.S. [2]. As claimed by FDA in the instructions for healthcare facilities [12], the contaminated FFRs are first collected in a primary collection bag and closed. Then, the primary collection bag is placed into the secondary collection bag and closed [39]. Finally, the secondary collection bag is disinfected by decontaminant such as ethanol and put into a carton for shipping. Therefore, two biohazard bags and one carton are required for collecting, packing, and shipping a

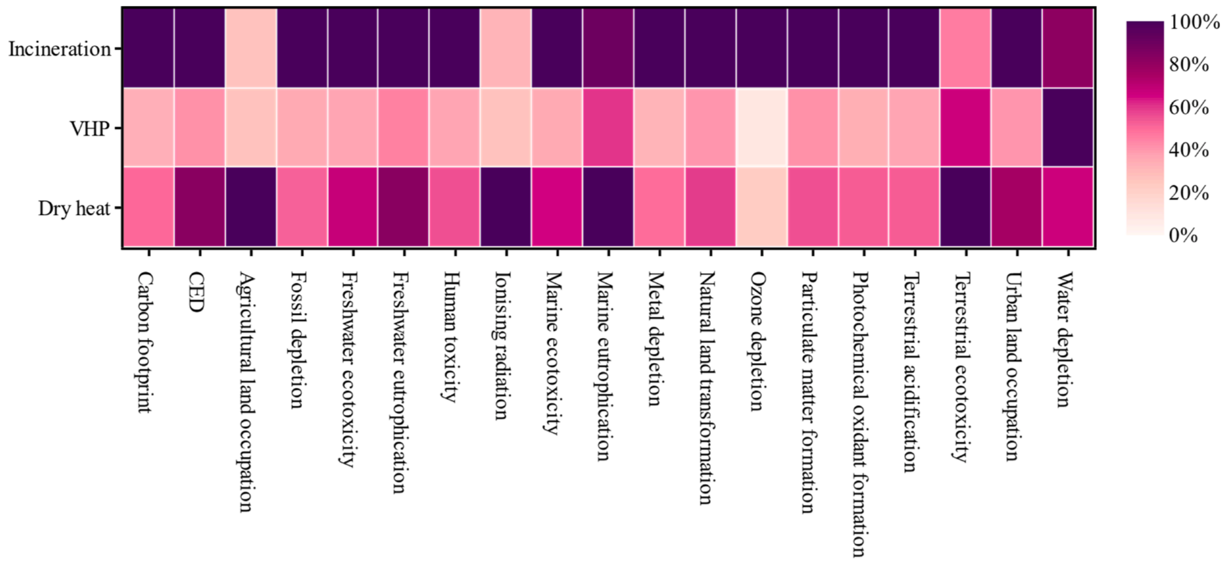

Fig. 3. Comparison across the midpoint indicators for the dry heat- and VHP-based multiple reuse cases and the single-use case. Colors indicate the sign of the result for each midpoint indicator. The darkness of the colors corresponds to the magnitude of the result for each midpoint indicator. Specifically, the percentages are computed based on the largest absolute value of the results for each midpoint indicator. Darker color indicates larger environmental impacts in each impact category.

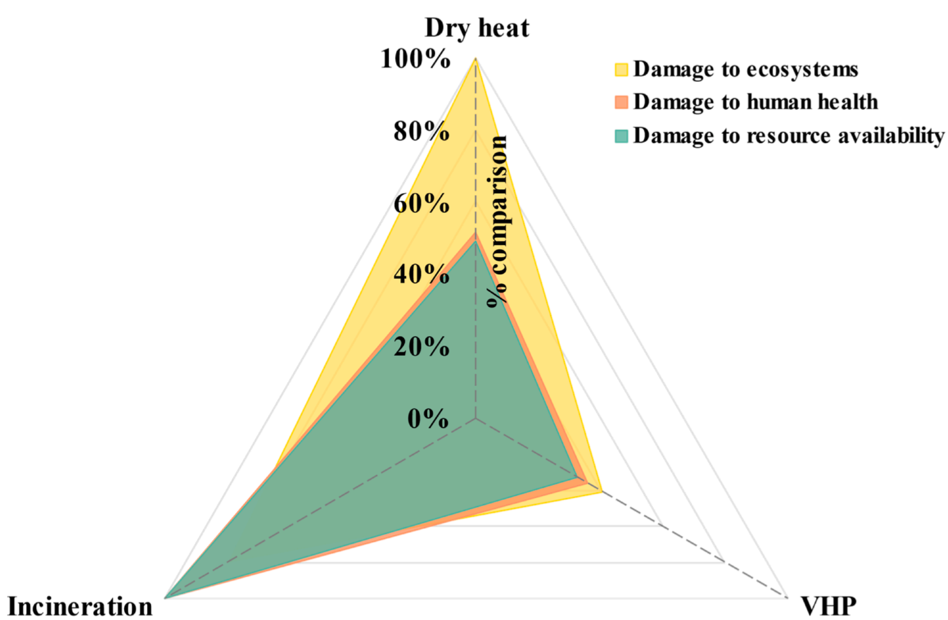

Fig. 4. Comparison among the dry heat- and VHP-based multiple reuse cases and the single-use case based on the three ReCiPe endpoint indicators per 1,000 used FFRs.

batch of FFRs to the decontamination system according to the U.S. CDC's instruction on the management of RMW in healthcare facilities. For the incineration of RMW, a reusable rigid container with proper labeling is permitted to contain the secondary biohazard bag to be shipped to the HMIWI [40]. Notably, the number of FFRs in each batch may vary. Therefore, we consider packing an average of 120 contaminated N95 masks with two 10-gallon (equivalent to 0.038 m^3) biohazard bags with 70% full and a carton of the same size as one box of 120 standard N95 respirators. During the decontamination process, the VHP decontamination system exposes the N95 masks to the vapor H_2O_2 without any shields. In contrast, the dry heat decontamination system requires the use of autoclave paper bags to protect the sterilizer and to indicate whether the desired temperature is reached [18].

2.3.3. Respirator storage and transportation

This subsection describes the storage and distribution of the used FFRs collected in the biohazard bags and decontaminated FFRs packed in cartons. Specifically, the used N95 masks are collected from the healthcare facilities and shipped to either the decontamination sites or the HMIWI by trucks specifically designed for medical waste transportation. Moreover, the incineration of waste respirators produces solid ash, which is further transported to landfilling [41]. After decontamination, the disinfected N95 masks are delivered to the healthcare facilities and reused [30]. According to the New York State Department of Environmental Conservation [42], most RMW are disposed of off-site. Thus, the waste respirators are assumed to be transported 80 km from the healthcare facilities to the HMIWI based on the distance from Ithaca, NY, to the nearest disposal site of a leading RMW management company

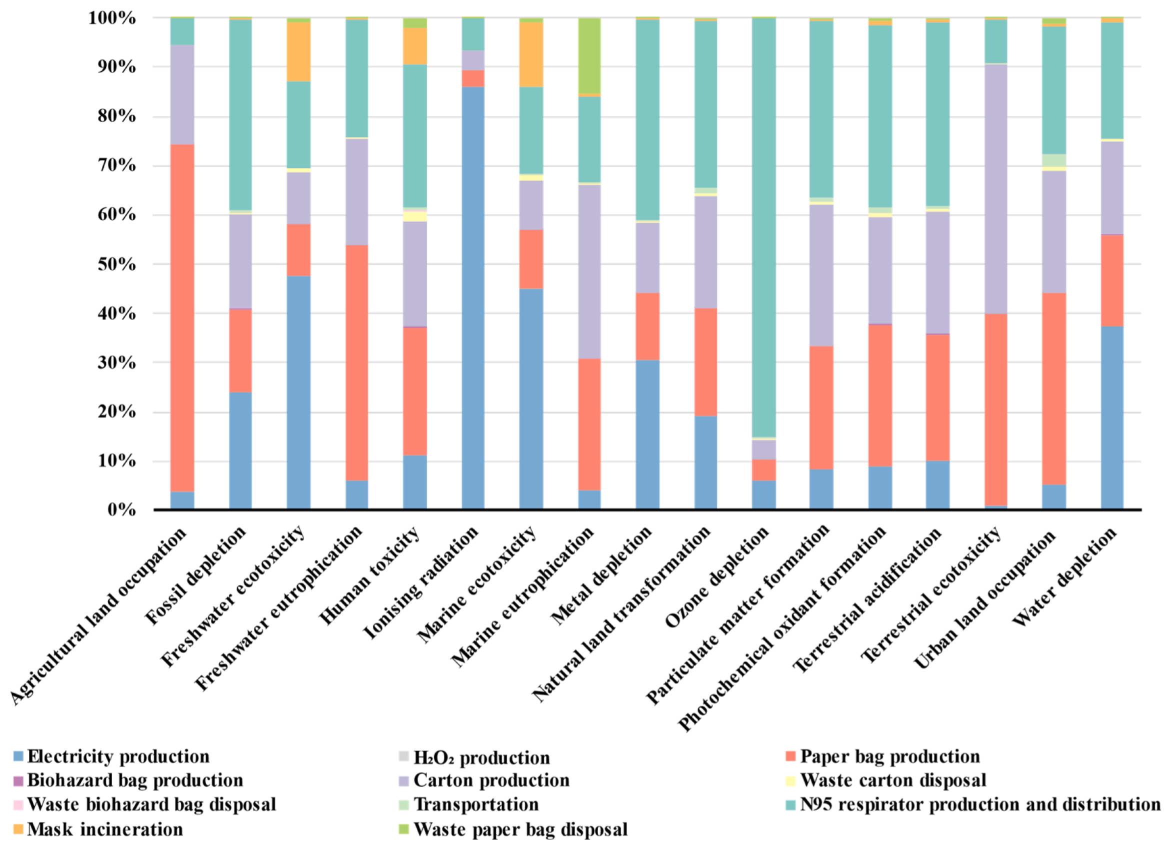

Fig. 5. Breakdowns of midpoint indicators for the dry heat-based multiple reuse case.

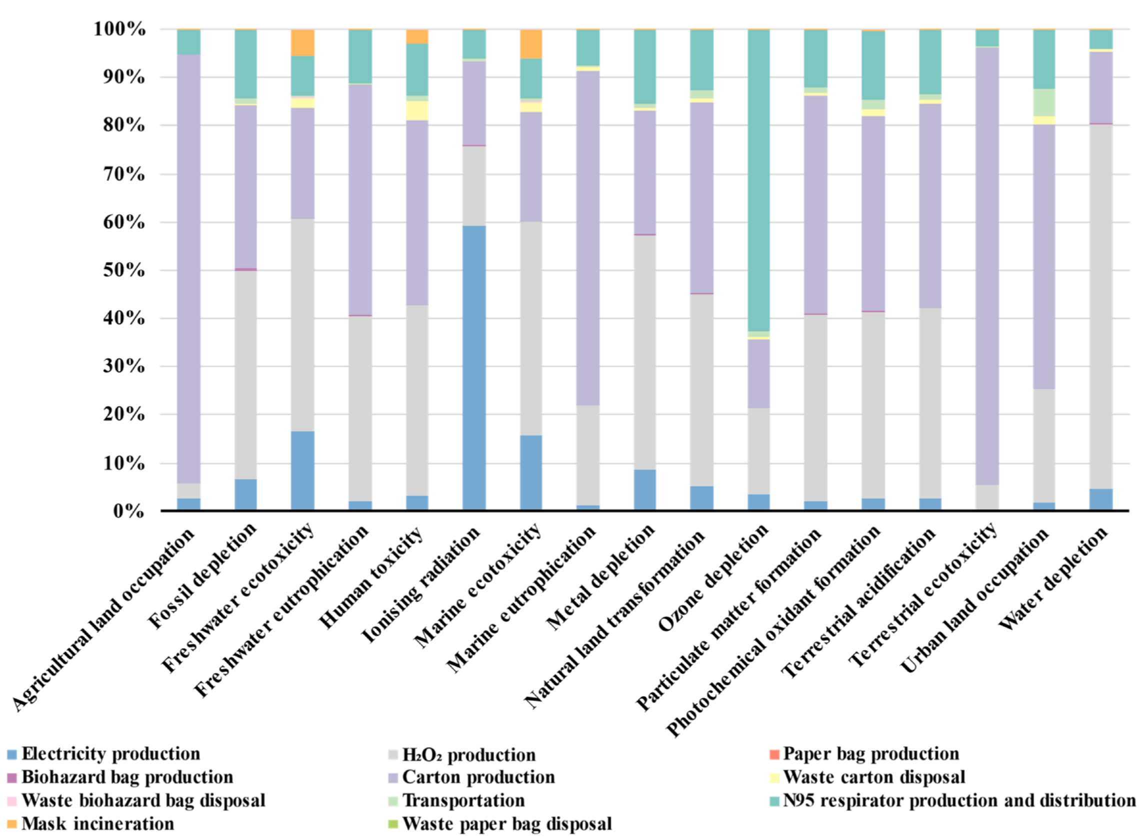

Fig. 6. Breakdowns of midpoint indicators for the VHP-based multiple reuse case.

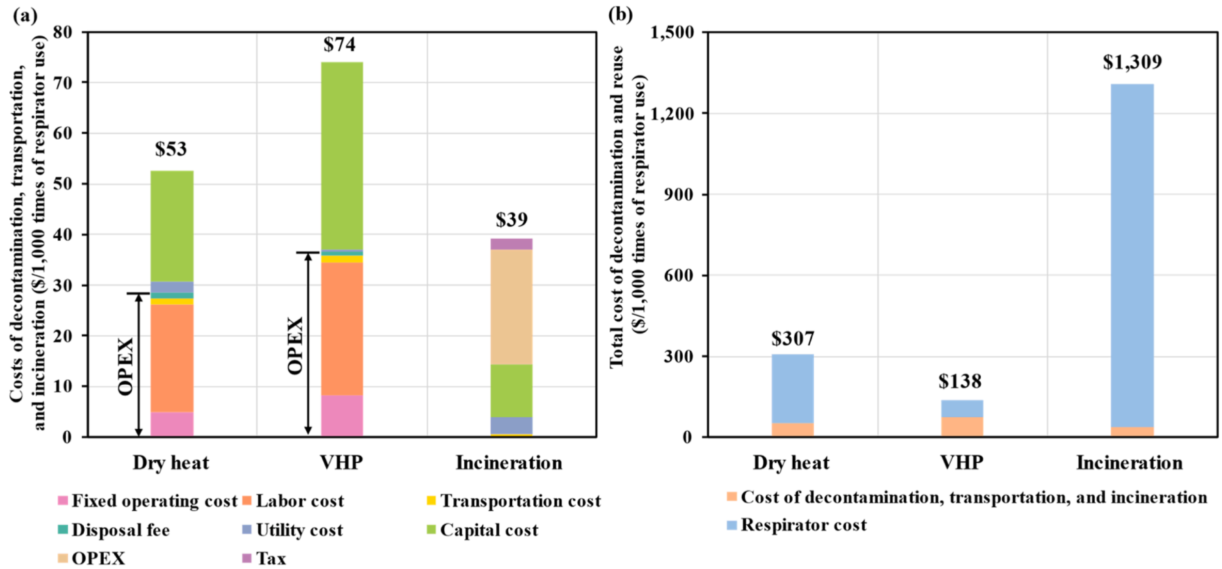

Fig. 7. TEA results of the dry-heat-based and VHP-based multiple reuse cases and the single-use case. (a) Breakdowns of the decontamination, transportation, and disposal costs for the three cases. (b) Breakdowns of the total cost, namely the respirator cost and the costs of decontamination, transportation, and incineration. Notably, the breakdowns of costs of decontamination, transportation, and incineration are presented in (a).

[43]. The transportation distance between the healthcare facilities and the decontamination sites is considered to be 80 km for a fair comparison across the three cases of FFR uses. Other auxiliary materials for packaging, including cartons and biohazard bags, are shipped back and forth with the respirators. Sensitivity analysis is conducted to assess the uncertainty in the transportation distance.

2.3.4. Respirator decontamination

This section aims to illustrate the material and energy input and output for the decontamination stage of the two multi-use cases. Common inputs for both dry heat and VHP decontamination systems are the contaminated N95 masks and the required energy for the system to operate. For the VHP method, the contaminated respirators are directly placed in the decontamination system and are contacted and penetrated by the vapor H_2O_2 to eliminate all biological contaminants. Vapor H_2O_2 is created by pushing liquid H_2O_2 through a nozzle, and it is circulated in the automated pressurized canister VHP system. For the dry heat method, each contaminated respirator is put into an autoclave paper bag before being replaced in the decontamination system. Then, the system is operated to heat the FFRs. Both decontamination systems output decontaminated FFRs and wastes. Disinfected respirators are returned back to the clinical sites for reuse, and the decontaminated autoclave paper bags are disposed of, as described in §2.3.5.

2.3.5. Reuse and disposal

The reuse and disposal stage focuses on treating the waste respirators and the disposed packaging materials. FFRs reaching the usage limit are sent to the HMIWI for disposal. For auxiliary materials, the carton and biohazard bags used to contain and pack the used N95 masks are considered biohazard wastes and sent to the HMIWI. The incineration of waste N95 respirators is assumed to be equivalent to the combination of incinerating each component of N95 masks, following a previous study [44]. The decontaminated autoclave paper bags and cartons used to deliver the new and decontaminated FFRs are disposed of as municipal solid waste, following the Environmental Protection Agency's data on the waste paper and paperboard management [45]. A transportation distance of 50 km is assumed for the collection of municipal solid waste following the literature [46].

2.4. Life cycle impact assessment

The LCIA phase of LCA translates the long list of LCI results into environmental impacts using characterization factors of different midpoint impact categories based on the selected LCIA methods. The LCIA results of midpoint impact categories can be further aggregated into endpoint areas of protection through environmental mechanisms. This work focuses on the Intergovernmental Panel on Climate Change (IPCC) 2013, CED, and the ReCiPe method from the hierarchist view to demonstrate and compare the carbon footprint, direct and indirect energy use, and a comprehensive list of impact categories, respectively. Specifically, the IPCC 2013 method reveals the current understanding of climate change by quantifying the global warming potential relative to CO_2 over the 100-time horizon [47]. CED assesses the direct and indirect energy use throughout the life cycle of a product [48]. Since the dry heat decontamination is energy-intensive, we consider CED as one of the key indicators to be addressed. Three endpoint indicators and seventeen midpoint indicators of ReCiPe are adopted to examine the severity across different aspects of environmental issues, including damage to resource availability, damage to ecosystems, and damage to human health, agricultural land occupation, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, metal depletion, natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, urban land occupation, and water depletion [49].

2.5. Interpretation

The LCIA results of the dry heat- and VHP-based multiple reuse cases convey key knowledge about the contributions of material and energy consumptions to various impact categories. Therefore, we quantify the LCA results and illustrate the breakdowns of carbon footprint, CED, and a broad set of environmental impact categories. Moreover, we identify the environmental hotspots and present the sensitivity analysis results on selected parameters, as shown in Table A5 and Table A6. Based on the interpretation of the LCIA results, more insightful directions are provided towards the practices of FFR decontamination under such pandemic conditions.

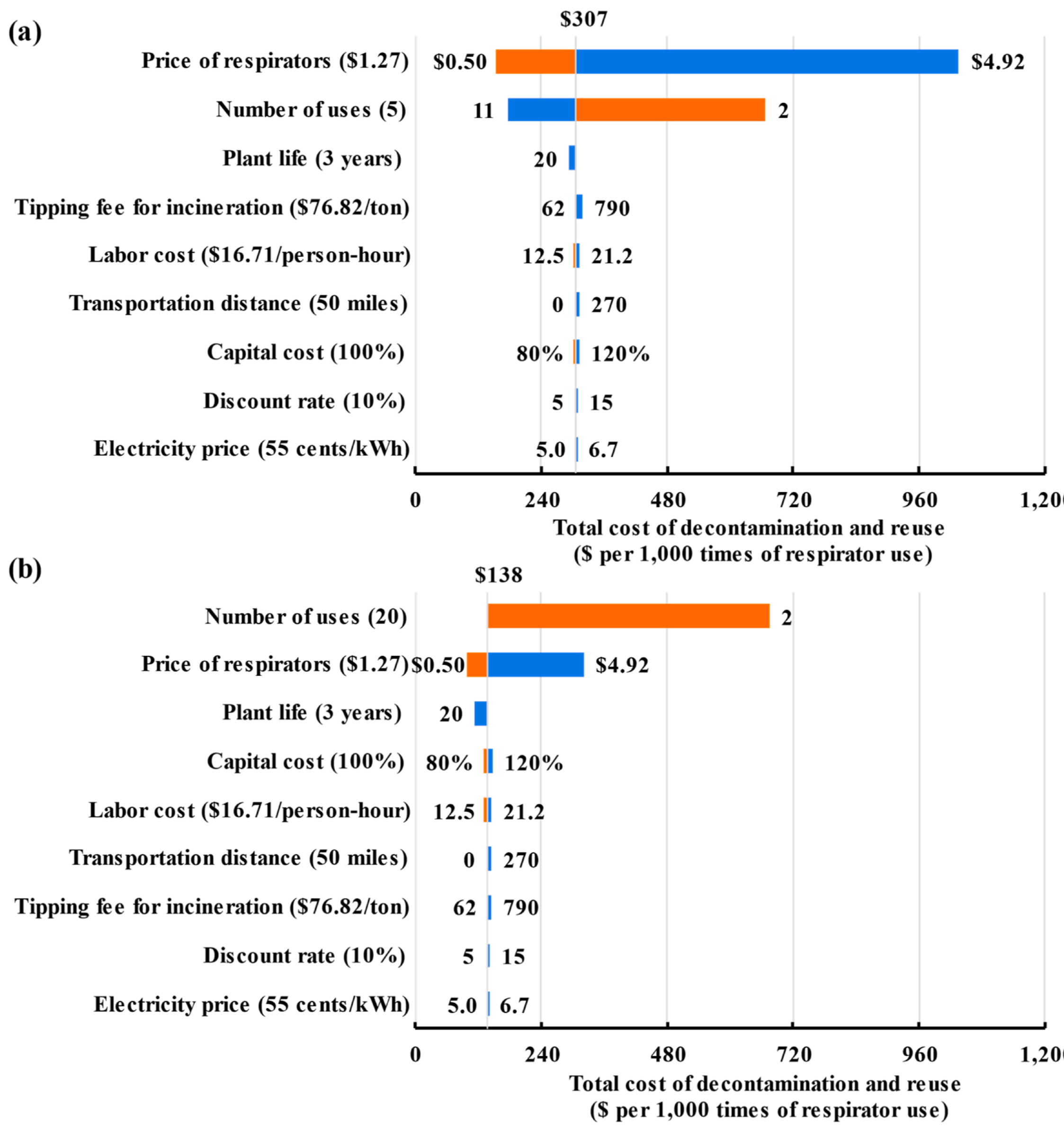

Fig. 8. Sensitivity analysis of the total cost estimates for the (a) dry heat- and (b) VHP-based multiple reuse cases.

2.6. Techno-economic analysis

To quantify the economic benefits of decontamination-and-reuse of respirators, we account for the total cost generated from the decontamination system, disposal fees for the waste respirators and the associated packaging materials, and the cost of purchasing new FFRs. The economic benefit adds up the annualized capital cost (*ACC*), fixed operating cost, labor cost, utility cost, disposal fees, transportation cost, and avoided cost of FFR purchase. A discount rate of 10% is selected to annualize the total capital cost (*TCC*), as shown in Eq. (1) [50].

$$ACC = \frac{TCC}{\frac{1}{r} - \frac{1}{r\cdot(1+r)^n}} \tag{1}$$

The total capital cost is calculated by Eq. (2) as the summation of the direct capital cost (*DCC*), indirect capital cost (*ICC*), working capital cost (*WCC*), and land cost (*LC*) [44].

$$TCC = DCC + ICC + WCC + LC \tag{2}$$

Each decontamination system consists of multiple parallel decontamination chambers, which are designed and built with specific sizes. Therefore, we do not consider the economies of scale for the decontamination systems. Instead, the unit economic performances of the decontamination systems based on the functional unit are independent of their sizes. For the dry heat decontamination system, we collect a commercial model's equipment and installation costs to calculate the direct capital cost [31]. Land cost is computed as 6% of the equipment cost [51]. Indirect capital cost is estimated as 123% of the direct capital cost, and working capital cost is estimated as 5% of the summation of the direct capital cost and land cost [51]. In terms of an enclosed VHP decontamination system with HEPA filter, we adopt the best available data and estimate the total capital costs from the original contract awarded to the Battelle Memorial Institute by the U.S. Department of Defense [52]. Fixed operating cost is the summation of operation labor cost and other fixed costs, including maintenance labor cost, overheads, maintenance materials, and taxes and insurance [50]. Operation labor cost is estimated from the number of workers based on the mean hourly wage of healthcare support occupations in NYS [53]. Other fixed costs are computed as 9% of the total capital cost [50]. Variable operating cost consists of utility cost, disposal fees, and transportation cost. Utility cost is based on the average industrial electricity price in 2020 for NYS [54].

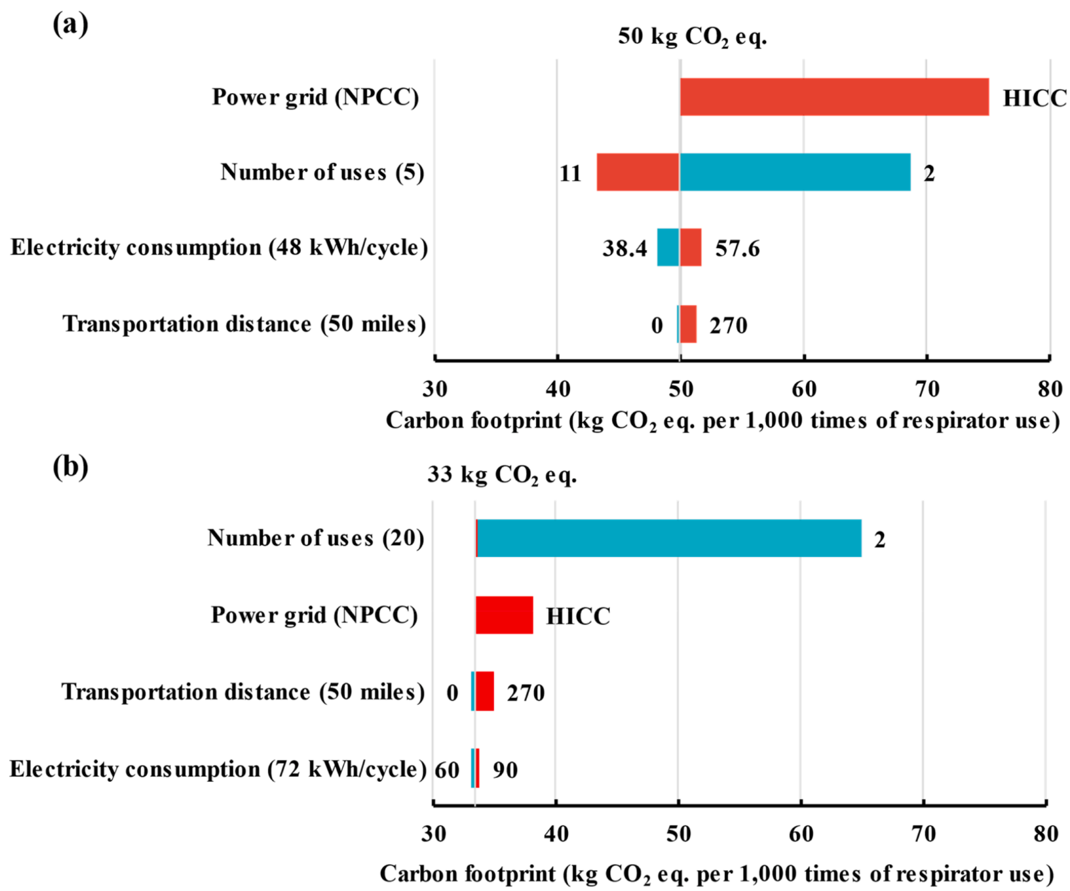

Fig. 9. Sensitivity analysis of the carbon footprint estimates for the (a) dry heat- and (b) VHP-based multiple reuse cases.

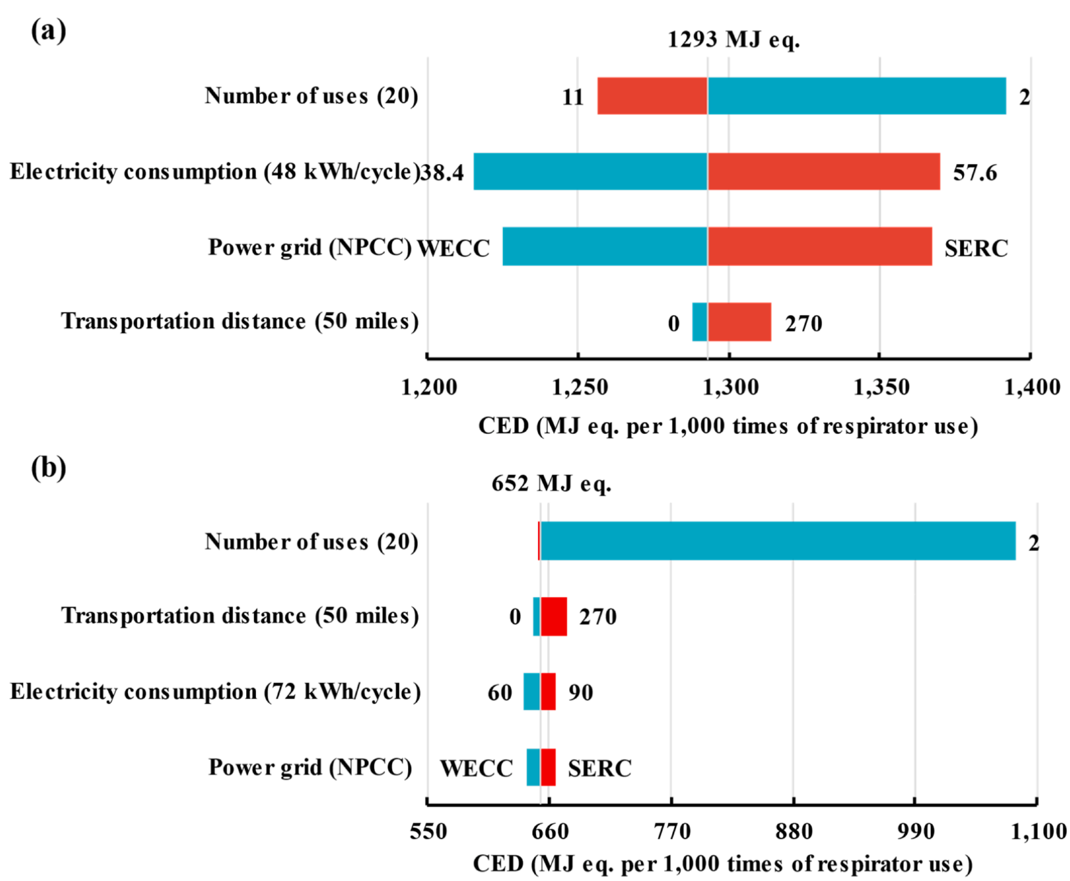

Fig. 10. Sensitivity analysis of the CED estimates for the (a) dry heat- and (b) VHP-based multiple reuse cases.

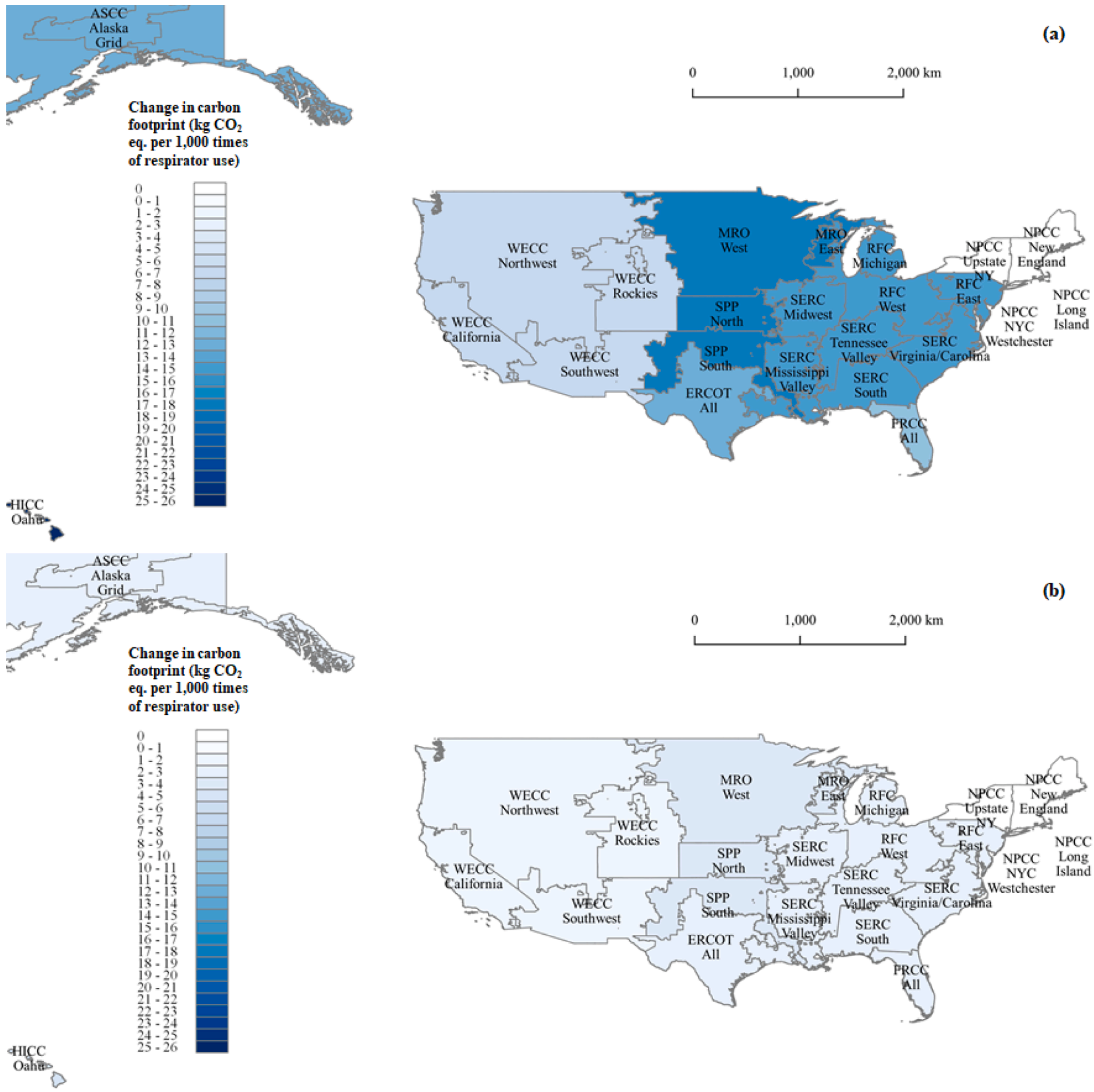

Fig. 11. Sensitivity analysis of the carbon footprint estimates for the (a) dry heat- and (b) VHP-based multiple reuse cases based on geospatial variation in the power grid, according to the NERC regions. NPCC is considered as the baseline to compute the differences in carbon footprint for each NERC region. Abbreviations: NPCC, Northeast Power Coordinating Council; WECC, Western Electricity Coordinating Council; MRO, Midwest Reliability Organization; SERC, Southeastern Electric Reliability Council; ERCOT, Electric Reliability Organization of Texas; FRCC, Florida Reliability Coordinating Council; RFC, Reliability First Corporation; ASCC, Alaska Systems Coordinating Council; HICC, Hawaiian Islands Coordinating Council; SPP, Southwest Power Pool.

Disposal fees [55] and transportation costs [44] are extracted from previous studies. Lastly, the decontaminated FFRs are not for sale, but they have economic benefits by substituting the new respirators bought from the market. To quantify the economic benefits of the decontamination-and-reuse of FFRs, we include the cost of FFRs. The recent price of an N95 mask is set as \$1.27, according to the current pricing from the 3 M Company [56]. However, N95 mask prices fluctuated significantly during the pandemic due to the high demand and supply shortages in these critical medical resources. The average price of an N95 mask before the COVID-19 pandemic was around \$0.50 [57], while it was inflated to as high as \$4.92 in the U.S. around the first half of 2020 [58]. Given the wide price range of N95 respirators over time, a sensitivity analysis is conducted to analyze the influence of this parameter on the TEA results, and the results are presented in §3.3. Details about the economic parameters are provided in Table A2 in Appendix.

3. Results

3.1. Environmental benefits of decontamination-and-reuse of N95 respirators

This section presents the breakdowns of carbon footprint, energy use, and other impact categories for the three use cases of respirators. As shown in Fig. 2, both multiple-use cases result in substantial environmental and energy benefits. Compared to the single-use case, the dry heat-based multiple reuse case reduces carbon footprint by 50% and CED by 17%. In comparison, the VHP-based multiple reuse case decreases carbon footprint by 67% and CED by 58%. Notably, decontamination-and-reuse of FFRs could achieve more emission

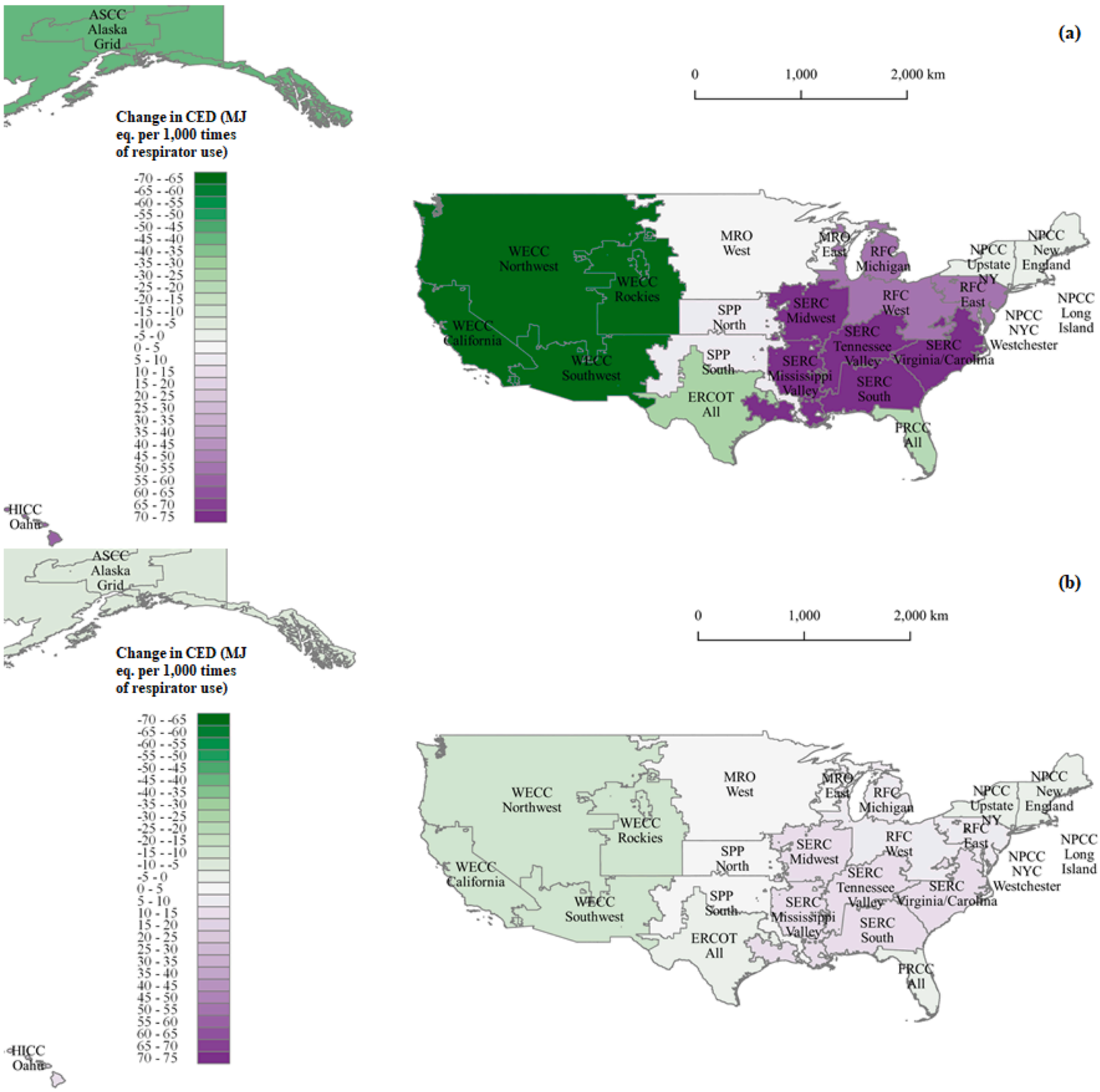

Fig. 12. Sensitivity analysis of the CED estimates for the (a) dry heat- and (b) VHP-based multiple reuse cases based on geospatial variation in the power grid, according to the NERC regions. NPCC is considered as the baseline to compute the differences in CED for each NERC region.

reduction benefits if the electrostatic charge step is not omitted for N95 mask production. This result is primarily because fewer N95 masks are produced to meet the function of 1,000 times of use/reuse due to the adoption of decontamination technologies. Consequently, fewer masks are incinerated at the end of life, leading to fewer greenhouse gas emissions. Furthermore, the results indicate higher environmental benefits of the VHP-based multiple reuse case in terms of the carbon footprint and CED. The N95 mask production and distribution contribute the most influentially to the superior environmental performance of the VHP decontamination method, allowing the use of each N95 mask 20 times. In contrast, the dry heat method is capable of decontaminating and reusing FFRs five times. Accordingly, 1,000 times of FFR use can be attained by sterilizing 50 respirators for a total of 950 times using the VHP method or disinfecting 200 respirators for 800 times using the dry heat method. This also causes 300% more waste respirators sent to the HMIWI. Furthermore, mask incineration becomes one of the key contributors to the carbon footprint (10%) of the dry heat-based multiple reuse case while it is minor to CED. Other than the production and distribution of more masks, the inferior environmental performance of the dry heat-based case can be attributed to the intensive consumption of electricity and autoclave paper bags for the dry heat method. Specifically, energy use and the extraction of raw materials, including pulpwood, printing ink, and packaging films, contribute to most carbon footprint and CED associated with autoclave bag production [59]. Among the carbon- and energy-intensive contributors of the VHP-based multiple reuse case, production of H_2O_2 and carton are dominant due to the large energy requirement for H_2O_2 production [60] and the unavoidable treatment of wastes and sludges from the carton production [61].

Fig. 3 presents the results for the midpoint indicators on a percentage basis. In detail, colors in the heat map indicate the sign of the result for each midpoint indicator. Darker color indicates more significant environmental impacts in each impact category. The percentages are computed based on the largest absolute value of the results for each midpoint indicator. It is worth noting that natural land transformation is the only impact category with negative environmental scores. This result can be primarily explained by the land transformation in the mineral extraction site and dumpsite during the N95 mask production. The results also show that the VHP-based multiple reuse case consistently outperforms the other two cases for most impact categories. Nevertheless, the VHP-based multiple reuse case achieves the worst performance in water depletion, primarily due to the intensive water use of H_2O_2 production. On the other hand, the dry heat-based multiple reuse case performs the worst in four impact categories, including agricultural land occupation, ionizing radiation, marine eutrophication, and terrestrial ecotoxicity, due to the intensive depletion of electricity and paper bags. Consequently, the dry heat-based multiple reuse case also results in the most damage to the ecosystems (Fig. 4). The single-use case performs the best for the terrestrial ecotoxicity, and this can be attributed to the large avoidance of cartons used for transporting the used FFRs to the decontamination systems.

Fig. 5 and Fig. 6 present the full-spectrum environmental profiles of 1,000 times of FFR use for the 17 midpoint impact categories. The results are presented on a percentage basis due to different units of environmental impacts for the assessed impact categories. The results show several influential contributors in most impact categories for both the dry heat- and VHP-based multiple reuse cases. For both multiple-use cases, the production of N95 masks and cartons are key contributors to most midpoint indicators. The production of non-woven polypropylene and polyester can explain over 50% of the environmental impacts associated with the N95 mask production for all impact categories except agricultural land occupation, natural land transformation, and water depletion. Specifically, the non-woven polypropylene is produced from the melting, extruding, and spraying of the polypropylene granules. The non-woven polyester is produced from the mechanical needle punching of the polyester fibers. The environmental burdens of the non-woven polypropylene and polyester are mainly from the energy use, extraction of crude oil, and emissions from raw material production, including CO_2, methane, the non-methane volatile organic compound, nitrogen oxides, sulfur dioxide, and particulates. The natural land transformation and water consumption of N95 mask production are mostly due to the production of aluminum strips. Other environmental hotspots are specific to the decontamination methods. In terms of the VHP-based case, H_2O_2 production is one of the most environmentally expensive contributors to most impact categories, as shown in Fig. 6. For the dry heat-based case, paper bag production and electricity consumption contribute considerably to most impact categories (Fig. 5). Due to the high penetration of nuclear power in the selected Northeast Power Coordinating Council (NPCC) power grid (over 30%) [62], electricity consumption accounts for the highest proportion of ionizing radiation for both multiple reuse cases. Remarkably, the environmental profile of electricity consumption varies geographically due to the divergent composition of energy sources for electric power production from region to region. Therefore, we conduct sensitivity analysis to evaluate the geographical variation in electricity consumption, as discussed in §3.3.

3.2. Economic benefits of decontamination-and-reuse of N95 respirators

To illustrate the economic benefits of used FFR decontamination technologies, we evaluate the total costs of the three cases, as presented in Fig. 7. Owing to the lower cost of purchasing new respirators, the total costs of using N95 masks 1,000 times for the dry-heat-based and VHP-based multiple reuse cases are 77% and 89% lower than that for the single-use case ($1,282 per 1000 times of use), respectively. This result suggests the remarkable economic benefits of reusing FFRs. It is worth mentioning that the superior capacity of the VHP-based multiple reuse case to decontaminate and reuse FFRs more times benefits not only its environmental performance but also its economic performance. Specifically, on the same basis of using respirators 1,000 times, the VHP method requires fewer respirators for providing the same function of 1000 times of respirator use than the dry heat method. Accordingly, fewer respirators are disposed of at the end of life. However, due to the low disposal cost (87 cents per 1,000 FFRs) for incineration, a larger number of FFR decontamination induces higher treatment costs. Therefore, there is a trade-off between environmental performances and decontamination costs. The reductions are modest compared to their total costs. In addition to the effect of the number of uses, the dry heat-based multiple reuse case costs less in terms of capital cost, fixed operating cost, and labor cost compared to the VHP-based case. Specifically, capital cost accounts for the highest proportion of the decontamination cost for both dry-heat-based (42%) and VHP-based (50%) multiple reuse cases. As the fixed operating cost is computed as a proportion of the total capital cost, the higher capital cost of the VHP decontamination system widens the gap between the decontamination costs of the two multiple-use cases. Moreover, labor cost is responsible for 40% of the decontamination cost in the dry heat-based case and 35% for the VHP-based case. This result suggests that FFR decontamination is a labor-intensive process.

3.3. Sensitivity analysis

This section performs sensitivity analysis to investigate the most influential parameters in terms of economic and environmental performances. As shown in Fig. 8, the most sensitive economic parameter is the N95 mask's price for the dry heat-based multiple reuse case, which was approximately $0.50 [57] before the COVID-19 pandemic and $4.92 in the middle of the pandemic [58]. With a higher respirator's price, the economic benefits of decontamination-and-reuse of FFRs become more prominent, and vice versa. The number of FFR uses is the most volatile economic parameter for the VHP-based multiple reuse cases, and it has the same effects on the economic and environmental performance because fewer respirators are needed for a larger number of FFR uses. The effects of other parameters are negligible on the TEA results for both multiple reuse cases. It is worth noting that the influence of capital cost is more prominent in the VHP-based multiple reuse cases due to its substantially higher capital cost.

The power grid and the number of FFR uses play the most critical roles in the sensitivity analysis in terms of the carbon footprint, as shown in Fig. 9 and Fig. 10. This result also suggests that it is more impactful to choose a decontamination method with the capability of increasing usage cycles than to select an energy-efficient decontamination model for mitigating climate change. In contrast to the carbon footprint results, the CED of the VHP-based multiple reuse case is insensitive to the geographic variation in the power grid. Moreover, both the carbon footprint and CED of the dry heat-based multiple reuse case are more sensitive to the changes in electricity consumption relative to the VHP-based multiple reuse case. Fig. 11 and Fig. 12 reveal the geographic variation of carbon footprint and CED according to the North American Electric Reliability Corporation (NERC) regions. NPCC is considered as the baseline to compute the increase in carbon footprint and CED for each NERC region. Consistently, the dry heat-based multiple reuse case is much more sensitive to the variation in power grids than the VHP-based multiple reuse case, especially for CED. Moreover, installing the decontamination system in the NPCC region is the most encouraging to mitigate carbon footprint. In terms of CED, the Western Electricity Coordinating Council (WECC) is the most energy-efficient grid to deploy the decontamination system.

3.4. Insights for policy makers and healthcare facilities

Disinfecting and reusing FFRs are crisis capacity strategies that could be implemented when the mask supply is not able to meet their utilization rates in healthcare facilities [1]. We find that decontaminate and reuse FFRs multiple times can provide substantial environmental and economic benefits. Further reductions in environmental impacts and costs associated with the FFR sterilization can be achieved if several current practices can be improved. First, it is economically favorable to decontaminate and reuse FFRs, especially under the acute shortage. The breakeven price of the N95 mask is $0.051 for the dry heat-based multiple reuse case and $0.065 for the VHP-based multiple reuse case. They are both much lower than the pre-pandemic price. When the actual N95 mask's price is above the breakeven price, it is economically viable to decontaminate and reuse them. For policy makers, it is critical to choose the technology with the maximum number of decontamination cycles. For healthcare facilities, choosing energy-efficient models for the sterilizers and building decontamination systems onsite are more economically and environmentally viable.

4. Conclusion

In this paper, we conducted the LCA and TEA for the dry-heat-based and VHP-based multiple reuse cases that could alleviate shortages of new FFRs in healthcare facilities. The energy and environmental performances of the decontamination-and-reuse cases were compared with the single-use case through carbon footprint, CED, and a full spectrum of midpoint and endpoint indicators. Compared to the single-use case, the dry heat-based multiple reuse cases reduced carbon footprint by 50% and CED by 17%, while the VHP-based multiple reuse case decreases carbon footprint by 66% and CED by 58%. The environmental benefits of the VHP-based multiple reuse case were highlighted in most impact categories. As for the economic benefits, the total costs of the dry-heat-based and VHP-based multiple reuse cases were 77% and 89% lower than that of the single-use case, respectively. Given the market price of new N95 masks, TEA results indicated strong economic viability for deploying both decontamination methods even under unfavorable conditions, such as shorter plant life, longer transportation distance, higher discount rate, and higher investments. The sensitivity analysis demonstrated the pronounced effect of the geographic variation of the power grid on the carbon footprint and CED of the dry heat-based multiple reuse cases due to its intensive energy use. Several practices could be adopted to further improve the energy, environmental, and economic performances of the decontamination systems by prioritizing the number of FFR uses when choosing among different decontamination technologies, properly choosing the energy-efficient decontamination models, and building decontamination systems onsite.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

None.

Appendix A

Tables A1-A8

Table A1
Material and energy input and output for the three cases [23,29,30,34,63].

Category	Component	Unit	Case		
			Dry heat	VHP	Single use
Input	N95 masks	kg	2.3	0.57	11.3
	Electricity	kWh	38.4	7.1	–
	Paper autoclave bag	kg	6.6	–	–
	Carton	kg	7.1	8.5	–
	Biohazard bag	kg	0.021	0.025	0.026
	H_2O_2	kg	–	9.1	–
	Transportation	km	80.5		
Output, to incineration	Waste paper autoclave bag	kg	0.35	–	–
	Waste carton	kg	2.6	3.1	–
	Waste biohazard bag	kg	0.021	0.025	0.026
	Waste N95 masks	kg	2.3	0.57	11.3
Output, to landfill	Waste paper autoclave bag	kg	1.4	–	–
	Waste carton	kg	0.46	0.55	–
Output, collection for recycling	Waste paper autoclave bag	kg	4.8	–	–
	Waste carton	kg	4.1	4.9	–

Table A2
Input parameters for the techno-economic analysis [30,44,51,53,54,63,64].

Item	Unit	Dry heat	VHP	Single use
Capacity	Number per cycle	1,000	10,000	–
Direct capital cost	$	450,000	2,561,301	–
Indirect capital cost	$	398,201		–
Working capital	$	23,471		–
Land cost	$	19,424	275,523	–
Discount rate	%	10		–
Transportation cost	$/(km-ton)	0.63		–
Fixed operating cost	$	80,199	255,314	–
Labor cost	$/person-hour	16.71	16.71	–
Utility cost	$/kWh for decontamination; $/kg for incineration	0.055		0.085
Annualized CAPEX	$/kg	–	–	0.27
Annualized OPEX	$/kg	–	–	0.58
Annualized taxes	$/kg	–	–	0.054

Table A3
Results of sensitivity analysis for total cost of the dry heat-based multiple reuse case ($/1,000 times of respirator use).

	Unit	Base case	Lower extreme	Higher extreme	Total cost for the base case	Total cost for lower extreme	Total cost for higher extreme
Price of N95 masks [57,58]	$	1.27	0.5	4.92	306.5	152.5	1036.5
Discount rate [44]	%	10	5	15	306.5	304.6	308.5
Transportation distance	km	80.5	0	434.5	306.5	305.3	312.2
Plant life	year	3	–	20	306.5	–	291.1
Capital cost [65]	%	100	80	120	306.5	301.2	311.9
Electricity price [54]	$/kWh	0.055	0.050	0.067	306.5	306.4	307.0
Disposal fee [55,66]	$/ton	76.82	62	790	306.5	306.3	318.0
Labor cost [53,67]	$/person-hour	16.71	12.50	21.18	306.5	301.2	312.2
Number of FFR uses [15]	–	5	2	11	306.5	668.2	175.0

Table A4
Results of sensitivity analysis for total cost of the VHP-based multiple reuse case ($/1,000 times of respirator use).

	Unit	Base case	Lower extreme	Higher extreme	Total cost for the base case	Total cost for lower extreme	Total cost for higher extreme
Price of N95 masks [57,58]	$	1.27	0.5	4.92	137.6	99.1	320.1
Discount rate [44]	%	10	5	15	137.6	134.4	140.9
Transportation distance	km	80.5	0	434.5	137.6	136.1	144.3
Plant life	year	3	–	20	137.6	–	111.3
Capital cost [65]	%	100	80	120	137.6	128.5	146.7
Electricity price [54]	$/kWh	0.055	0.050	0.067	137.6	137.6	137.7
Disposal fee [55,66]	$/ton	76.82	62	790	137.6	137.5	144.1
Labor cost [53,67]	$/person-hour	16.71	12.50	21.18	137.6	131.0	144.6
Number of FFR uses [1]	–	20	2	–	137.6	674.4	–

Table A5
Results of sensitivity analysis for carbon footprint (kg CO_2 eq./1,000 times of respirator use) and CED (MJ eq./1,000 times of respirator use) of the dry heat-based multiple reuse case.

	Unit	Base case	Lower extreme (for carbon footprint/CED)	Higher extreme (for carbon footprint/CED)	Carbon footprint for the base case	Carbon footprint for lower extreme	Carbon footprint for higher extreme	CED for the base case	CED for low extreme	CED for higher extreme
Transportation distance	km	80.5	0	434.5	52.0	51.7	53.2	1309.4	1304.9	1329.2
Number of FFR uses [15]	–	5	2	11	52.0	73.8	44.0	1309.4	1434.0	1264.0
Power grid	%	NPCC	-/HICC	WECC/SERC	52.0	–	77.2	1309.4	1242.6	1384.8
Electricity consumption	kWh/cycle	48	38.4	57.6	52.0	50.2	53.8	1309.4	1232.2	1386.7

Table A6
Results of sensitivity analysis for carbon footprint (kg CO_2 eq./1,000 times of respirator use) and CED (MJ eq./1,000 times of respirator use) of the VHP -based multiple reuse case.

	Unit	Base case	Lower extreme (for carbon footprint/CED)	Higher extreme (for carbon footprint/CED)	Carbon footprint for the base case	Carbon footprint for lower extreme	Carbon footprint for higher extreme	CED for the base case	CED for low extreme	CED for higher extreme
Transportation distance	km	80.5	0	434.5	33.9	33.6	35.3	655.3	650.4	677.2
Number of FFR uses [1]	–	5	2	11	33.9	70.1	33.8	655.3	1122.6	652.9
Power grid	%	NPCC	-/HICC	WECC/SERC	33.9	–	38.6	655.3	643.3	669.7
Electricity consumption	kWh/cycle	75	60	90	33.9	33.6	34.3	655.3	641.0	669.6

Table A7
Characterization factor for the life cycle assessment [41].

Item	Ecoinvent process	Unit	Carbon footprint (kg CO_2 Eq)	CED (MJ eq.)	Agricultural land occupation ($m^2 \times$ year)	Fossil depletion (kg oil eq.)	Freshwater ecotoxicity (kg 1,4-DCB eq.)	Freshwater eutrophication (kg P eq.)	Human toxicity (kg 1,4-DCB eq.)	Ionising radiation (kg U-235 eq.)	Marine ecotoxicity (kg 1,4-DCB eq.)	Marine eutrophication (kg N eq.)	Metal depletion (kg Fe eq.)	Natural land transformation (m^2)	Ozone depletion (kg CFC-11 eq.)	Particulate matter formation (kg PM10 eq.)	Photochemical oxidant formation (kg NMVOC eq.)	Terrestrial acidification (kg SO_2 eq.)	Terrestrial ecotoxicity (kg 1,4-DCB eq.)	Urban land occupation ($m^2 \times$ year)	Water depletion (m^3 water eq.)
Autoclave paper bag	market for paper sack, RoW	kg	1.3E+00	5.3E+01	5.8E+00	4.2E-01	3.0E-02	1.3E-03	5.6E-01	8.3E-02	2.9E-02	1.3E-03	3.0E-02	−8.5E-05	9.5E-08	3.2E-03	7.1E-03	6.4E-03	6.8E-03	4.2E-02	1.7E-02
Biohazard bag	polyethylene production, high density, granulate, RoW	kg	2.3E+00	8.0E+01	3.7E-02	1.9E+00	3.2E-02	4.4E-04	3.6E-01	5.5E-02	2.8E-02	3.0E-04	4.8E-02	−6.0E-05	3.7E-08	3.0E-03	8.0E-03	7.1E-03	6.2E-05	7.1E-03	2.2E-02
Biohazard bag	polyethylene production, high density, granulate, recycled, US	kg	6.9E-01	9.8E+00	2.9E-02	1.9E-01	4.8E-02	3.2E-04	3.3E-01	1.1E-01	4.3E-02	5.7E-04	3.3E-02	−1.3E-04	3.6E-08	1.9E-03	1.8E-03	1.7E-03	8.6E-04	2.1E-02	3.2E-03
Biohazard bag	extrusion, plastic film, RoW	kg	6.2E-01	1.0E+01	2.3E-01	1.8E-01	9.8E-03	2.5E-04	2.0E-01	5.4E-02	8.7E-03	2.7E-04	7.3E-03	−4.4E-05	1.9E-08	1.6E-03	1.7E-03	2.4E-03	3.4E-04	7.9E-03	2.0E-02
Carton	market for folding boxboard carton, RoW	kg	2.4E+00	6.2E+01	2.7E+00	7.1E-01	3.9E-02	8.6E-04	7.6E-01	1.9E-01	3.4E-02	1.1E-03	4.2E-02	−1.4E-04	1.2E-07	6.9E-03	7.9E-03	9.8E-03	5.9E-03	3.5E-02	2.6E-02
Carton	market for corrugated board box, RoW	kg	1.1E+00	2.1E+01	1.0E+00	3.3E-01	2.2E-02	4.1E-04	2.8E-01	4.4E-02	1.8E-02	1.8E-03	2.3E-02	−5.5E-05	7.3E-08	1.9E-03	3.7E-03	4.0E-03	9.2E-03	2.0E-02	1.1E-02
Waste PE	treatment of waste polyethylene, municipal incineration, RoW	kg	3.0E+00	3.1E-01	5.3E-04	8.0E-03	1.1E-01	3.7E-06	6.8E-01	5.6E-04	1.1E-01	3.5E-05	1.2E-03	−1.7E-06	2.0E-09	1.2E-04	4.9E-04	3.0E-04	3.0E-04	2.9E-04	2.0E-03
Waste carton	treatment of waste paperboard, municipal incineration, RoW	kg	3.2E-02	2.5E-01	6.2E-04	6.1E-03	6.2E-03	4.0E-06	1.2E-01	7.5E-04	5.6E-03	4.3E-05	1.2E-03	−1.6E-06	2.4E-09	8.9E-05	3.1E-04	2.1E-04	5.1E-06	2.5E-04	1.6E-03
Waste carton	treatment of waste paperboard, inert material landfill, RoW	kg	5.3E-03	1.6E-01	5.0E-04	3.6E-03	3.7E-05	4.9E-07	6.3E-04	6.6E-04	3.4E-05	1.9E-06	1.2E-04	−2.6E-06	1.7E-09	1.8E-05	5.5E-05	3.8E-05	5.4E-07	8.1E-04	1.1E-05
Waste paper bag	treatment of waste paperboard, municipal incineration, RoW	kg	3.2E-02	2.5E-01	6.2E-04	6.1E-03	6.2E-03	4.0E-06	1.2E-01	7.5E-04	5.6E-03	4.3E-05	1.2E-03	−1.6E-06	2.4E-09	8.9E-05	3.1E-04	2.1E-04	5.1E-06	2.5E-04	1.6E-03
Waste paper bag	treatment of waste packaging paper, sanitary landfill, GLO	kg	1.1E+00	4.4E-01	1.7E-03	9.1E-03	1.1E-02	1.6E-05	1.6E-01	2.8E-03	1.0E-02	3.6E-03	5.6E-04	−4.7E-06	3.1E-09	8.3E-05	5.3E-04	1.8E-04	4.6E-06	4.3E-03	1.1E-04
Transportation	market for transport, freight, lorry, unspecified, RoW	tkm	1.4E-01	2.2E+00	1.4E-03	5.0E-02	1.0E-03	1.1E-05	3.8E-02	9.6E-03	1.3E-03	3.1E-05	2.5E-03	−1.3E-05	2.4E-08	3.1E-04	8.6E-04	5.8E-04	6.5E-05	9.2E-03	2.1E-04
Transportation	market for transport, freight train, US	tkm	5.7E-02	8.0E-01	1.4E-03	1.8E-02	6.0E-04	7.0E-06	7.4E-03	3.8E-03	5.6E-04	2.8E-05	3.1E-03	−6.0E-06	7.8E-09	2.1E-04	7.6E-04	4.6E-04	3.6E-06	2.4E-03	1.3E-04
H2O2	market for hydrogen peroxide, without water, in 50% solution state, RoW	kg	1.5E+00	2.3E+01	4.8E-02	5.4E-01	4.8E-02	4.1E-04	4.1E-01	8.0E-02	4.2E-02	4.6E-04	5.0E-02	−7.7E-05	1.0E-07	2.7E-03	4.4E-03	5.0E-03	4.5E-04	9.9E-03	7.4E-02

(continued on next page)

Table A7 (*continued*)

Item	Ecoinvent process	Unit	Carbon footprint (kg CO_2 Eq)	CED (MJ eq.)	Agricultural land occupation ($m^2 \times$ year)	Fossil depletion (kg oil eq.)	Freshwater ecotoxicity (kg 1,4-DCB eq.)	Freshwater eutrophication (kg P eq.)	Human toxicity (kg 1,4-DCB eq.)	Ionising radiation (kg U-235 eq.)	Marine ecotoxicity (kg 1,4-DCB eq.)	Marine eutrophication (kg N eq.)	Metal depletion (kg Fe eq.)	Natural land transformation (m^2)	Ozone depletion (kg CFC-11 eq.)	Particulate matter formation (kg PM10 eq.)	Photochemical oxidant formation (kg NMVOC eq.)	Terrestrial acidification (kg SO_2 eq.)	Terrestrial ecotoxicity (kg 1,4-DCB eq.)	Urban land occupation ($m^2 \times$ year)	Water depletion (m^3 water eq.)
Waste N95 mask	treatment of waste polypropylene, municipal incineration, RoW	kg	3.0E+00	3.1E-01	5.3E-04	8.0E-03	1.1E-01	3.7E-06	6.8E-01	5.6E-04	1.1E-01	3.5E-05	1.2E-03	−1.7E-06	2.0E-09	1.2E-04	4.9E-04	3.0E-04	3.0E-04	2.9E-04	2.0E-03
Waste N95 mask	treatment of waste polyethylene terephthalate, municipal incineration, RoW	kg	2.1E+00	3.0E-01	4.4E-04	7.9E-03	6.6E-02	3.2E-06	4.8E-01	4.6E-04	6.5E-02	9.3E-05	1.2E-03	−1.5E-06	1.8E-09	1.3E-04	5.1E-04	3.1E-04	2.2E-04	2.3E-04	1.6E-03
Waste N95 mask	treatment of waste rubber, unspecified, municipal incineration, RoW	kg	3.2E+00	4.6E-01	1.5E-03	1.1E-02	3.7E-02	9.0E-06	2.0E-01	1.7E-03	3.0E-02	2.4E-05	1.6E-03	−2.8E-06	5.2E-09	1.4E-04	4.8E-04	3.6E-04	4.1E-05	6.3E-04	2.1E-03
Waste N95 mask	treatment of scrap aluminium, municipal incineration, RoW	kg	1.4E-02	2.8E-01	9.6E-04	6.4E-03	1.5E-03	2.8E-06	1.1E-02	1.1E-03	1.3E-03	4.1E-06	1.2E-03	−4.2E-06	2.6E-09	4.3E-05	1.0E-04	6.9E-05	3.1E-06	2.0E-03	8.9E-04
Waste N95 mask	treatment of scrap steel, municipal incineration, RoW	kg	1.1E-02	2.0E-01	6.8E-04	4.6E-03	1.7E+00	1.3E-05	1.8E+00	8.2E-04	1.5E+00	3.3E-06	1.1E-03	−3.1E-06	1.8E-09	3.4E-05	7.8E-05	5.1E-05	2.1E-06	1.3E-03	9.1E-04
Waste N95 mask	treatment of waste polyurethane, municipal incineration, RoW	kg	2.7E+00	1.6E+00	2.4E-03	4.4E-02	5.6E-02	1.4E-05	3.1E-01	2.2E-03	4.9E-02	8.1E-04	2.3E-03	−3.8E-06	1.1E-08	7.0E-04	3.0E-03	1.8E-03	1.3E-04	6.6E-04	2.3E-03
N95 mask	market for textile, non woven polypropylene, GLO	kg	2.9E+00	9.3E+01	7.4E-02	2.1E+00	5.7E-02	7.6E-04	6.1E-01	2.1E-01	5.1E-02	5.0E-04	6.5E-02	−9.7E-05	9.7E-08	4.4E-03	9.9E-03	9.6E-03	1.3E-04	1.9E-02	2.6E-02
N95 mask	market for textile, non woven polyester, GLO	kg	5.4E+00	1.2E+02	5.8E-01	2.6E+00	1.3E-01	1.5E-03	1.5E+00	4.1E-01	1.1E-01	2.1E-03	2.9E-01	−3.0E-04	1.1E-05	1.0E-02	2.4E-02	2.2E-02	5.1E-04	5.1E-02	6.1E-02
N95 mask	market for synthetic rubber, GLO	kg	2.7E+00	8.7E+01	2.2E-01	1.9E+00	7.0E-02	8.3E-04	8.1E-01	3.9E-01	6.1E-02	4.9E-04	1.4E-01	−1.5E-04	5.2E-07	5.3E-03	1.3E-02	1.2E-02	1.9E-04	2.5E-02	4.4E-02
N95 mask	market for aluminium, primary, ingot, RoW	kg	2.2E+01	2.3E+02	4.3E-01	5.0E+00	2.9E-01	6.7E-03	6.8E+00	2.7E-01	2.7E-01	3.9E-03	2.1E-01	−1.3E-03	5.5E-07	5.2E-02	7.2E-02	1.1E-01	5.4E-04	1.4E-01	7.6E-02
N95 mask	market for sheet rolling, aluminium, GLO	kg	6.5E-01	9.4E+00	2.3E-02	1.9E-01	1.7E-02	2.5E-04	2.0E-01	5.8E-02	1.5E-02	1.3E-04	8.0E-03	−4.2E-05	2.4E-08	1.4E-03	2.2E-03	2.5E-03	4.3E-05	3.3E-03	4.6E-03
N95 mask	market for metal working, average for aluminium product manufacturing, GLO	kg	4.1E+00	5.0E+01	1.4E-01	1.0E+00	3.5E-01	1.4E-03	1.4E+00	2.5E-01	3.1E-01	1.2E-03	8.6E-02	−5.5E-04	1.9E-07	8.8E-03	1.2E-02	1.8E-02	5.9E-04	4.9E-02	2.6E-02
N95 mask		kg	1.6E+00	2.1E+01	6.2E-02	4.3E-01	6.6E-02	8.1E-04	7.9E-01	1.2E-01	6.3E-02	7.4E-04	1.2E+00	−1.6E-04	6.6E-08	4.5E-03	6.8E-03	5.7E-03	1.3E-04	2.3E-02	2.3E-02

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Table A7 (*continued*)

Item	Ecoinvent process	Unit	Carbon footprint (kg CO_2 Eq)	CED (MJ eq.)	Agricultural land occupation ($m^2 \times$ year)	Fossil depletion (kg oil eq.)	Freshwater ecotoxicity (kg 1,4-DCB eq.)	Freshwater eutrophication (kg P eq.)	Human toxicity (kg 1,4-DCB eq.)	Ionising radiation (kg U-235 eq.)	Marine ecotoxicity (kg 1,4-DCB eq.)	Marine eutrophication (kg N eq.)	Metal depletion (kg Fe eq.)	Natural land transformation (m^2)	Ozone depletion (kg CFC-11 eq.)	Particulate matter formation (kg PM10 eq.)	Photochemical oxidant formation (kg NMVOC eq.)	Terrestrial acidification (kg SO_2 eq.)	Terrestrial ecotoxicity (kg 1,4-DCB eq.)	Urban land occupation ($m^2 \times$ year)	Water depletion (m^3 water eq.)
	market for steel, low-alloyed, hot rolled, GLO																				
N95 mask	market for sheet rolling, steel, GLO	kg	3.8E-01	5.3E+00	1.9E-02	1.1E-01	2.4E-02	1.6E-04	1.4E-01	3.2E-02	2.2E-02	7.5E-05	6.0E-02	−2.9E-05	1.6E-08	9.3E-04	1.5E-03	1.3E-03	1.6E-05	3.7E-03	7.5E-03
N95 mask	market for metal working, average for steel product manufacturing, GLO	kg	1.9E+00	2.7E+01	8.8E-02	5.4E-01	7.9E-02	7.4E-04	6.5E-01	2.1E-01	7.2E-02	9.5E-04	2.9E-01	−3.4E-04	1.1E-07	3.8E-03	5.0E-03	6.1E-03	5.3E-04	3.6E-02	1.6E-02
N95 mask	market for polyurethane, flexible foam, RoW	kg	5.5E+00	1.1E+02	2.3E-02	2.3E+00	3.6E-02	5.4E-04	4.0E-01	3.0E-02	3.2E-02	6.2E-03	4.8E-02	−4.5E-05	1.1E-07	1.0E-02	1.8E-02	2.1E-02	4.6E-04	1.2E-02	1.2E-01
N95 mask	market for acrylic binder, without water, in 34% solution state, RoW	kg	1.7E+00	4.1E+01	8.5E-02	9.2E-01	5.3E-02	5.5E-04	5.8E-01	1.2E-01	4.7E-02	2.9E-04	8.7E-02	−1.0E-04	1.3E-07	3.2E-03	6.4E-03	6.8E-03	1.7E-04	1.8E-02	2.7E-02
N95 mask	market for printing ink, offset, without solvent, in 47.5% solution state, RoW	kg	4.2E+00	7.9E+01	1.6E+00	1.4E+00	6.8E-02	8.3E-04	6.9E-01	2.1E-01	5.7E-02	5.0E-03	1.2E-01	−1.4E-04	1.7E-06	6.7E-03	1.1E-02	1.2E-02	2.3E-02	2.8E-02	2.0E-02
Electricity	market for electricity, low voltage, US-NPCC	kWh	2.4E-01	1.0E+01	5.5E-02	1.0E-01	2.3E-02	2.8E-05	4.2E-02	3.6E-01	1.9E-02	3.5E-05	1.1E-02	−1.3E-05	2.4E-08	1.8E-04	3.8E-04	4.3E-04	3.0E-05	9.8E-04	5.8E-03
Electricity	market for electricity, low voltage, US-WECC	kWh	4.1E-01	8.3E+00	2.5E-02	1.3E-01	2.9E-02	4.3E-04	2.8E-01	7.4E-02	2.5E-02	1.2E-04	1.1E-02	−1.5E-05	1.7E-08	1.5E-03	6.8E-04	7.8E-04	3.2E-05	2.4E-03	3.1E-03
Electricity	market for electricity, low voltage, US-TRE	kWh	5.6E-01	9.4E+00	5.7E-03	1.9E-01	3.4E-02	7.0E-04	4.3E-01	9.7E-02	2.9E-02	1.7E-04	1.1E-02	−1.1E-05	2.8E-08	2.8E-03	5.9E-04	1.2E-03	3.6E-05	9.2E-04	1.5E-03
Electricity	market for electricity, low voltage, US-SERC	kWh	6.2E-01	1.2E+01	5.8E-02	1.9E-01	3.0E-02	4.4E-04	3.0E-01	2.4E-01	2.5E-02	1.3E-04	1.2E-02	−2.2E-05	2.5E-08	1.4E-03	8.8E-04	1.5E-03	3.6E-05	2.6E-03	2.3E-03
Electricity	market for electricity, low voltage, US-RFC	kWh	6.1E-01	1.1E+01	1.4E-02	1.7E-01	2.8E-02	3.5E-04	2.5E-01	2.8E-01	2.4E-02	1.2E-04	1.2E-02	−2.4E-05	1.8E-08	1.1E-03	9.9E-04	1.9E-03	2.7E-05	2.6E-03	2.2E-03
Electricity	market for electricity, low voltage, US-MRO	kWh	6.9E-01	1.0E+01	2.8E-02	1.8E-01	3.9E-02	1.1E-03	6.7E-01	7.1E-02	3.5E-02	2.6E-04	1.1E-02	−3.2E-05	1.3E-08	4.1E-03	1.1E-03	2.3E-03	2.3E-05	2.2E-03	3.6E-03
Electricity	market for electricity, low voltage, US-HICC	kWh	8.9E-01	1.2E+01	5.9E-03	2.6E-01	2.8E-02	4.0E-04	3.3E-01	3.9E-02	2.6E-02	2.5E-04	1.1E-02	−2.9E-05	1.1E-07	3.0E-03	3.2E-03	5.8E-03	9.8E-05	3.0E-03	4.0E-03
Electricity	market for electricity, low voltage, US-FRCC	kWh	5.2E-01	9.5E+00	3.6E-02	2.0E-01	2.5E-02	9.3E-05	8.1E-02	1.2E-01	2.0E-02	5.2E-05	1.1E-02	−1.2E-05	4.0E-08	2.9E-04	7.5E-04	9.1E-04	4.8E-05	1.7E-03	1.5E-03
Electricity	market for electricity, low voltage, US-ASCC	kWh	5.7E-01	9.0E+00	5.6E-03	2.0E-01	2.8E-02	3.4E-04	2.5E-01	8.6E-03	2.4E-02	1.3E-04	1.0E-02	−2.4E-05	5.0E-08	1.8E-03	1.3E-03	2.1E-03	5.2E-05	2.0E-03	4.9E-03
Electricity	SPP[68]	kWh	6.8E-01	1.0E+01	3.1E-02	1.8E-01	3.8E-02	9.8E-04	6.2E-01	9.0E-02	3.3E-02	2.5E-04	1.1E-02	−3.0E-05	1.5E-08	3.8E-03	1.1E-03	2.2E-03	2.5E-05	2.2E-03	3.4E-03

Table A8
Characterization factor for the life cycle assessment [41].

Item	Ecoinvent process	Unit	Damage to resource availability (Points)	Damage to ecosystems (Points)	Damage to human health (Points)
Autoclave paper bag	market for paper sack, RoW	kg	5.7E-02	2.5E-01	6.0E-02
Biohazard bag	polyethylene production, high density, granulate, RoW	kg	2.2E-01	4.2E-02	8.5E-02
Biohazard bag	polyethylene production, high density, granulate, recycled, US	kg	2.8E-02	1.4E-02	3.6E-02
Biohazard bag	extrusion, plastic film, RoW	kg	2.3E-02	2.0E-02	2.8E-02
Carton	market for folding boxboard carton, RoW	unit	8.9E-02	1.5E-01	1.2E-01
Carton	market for corrugated board box, RoW	kg	4.2E-02	7.0E-02	4.3E-02
Waste PE	treatment of waste polyethylene, municipal incineration, RoW	kg	1.4E-03	5.3E-02	9.4E-02
Waste carton	treatment of waste paperboard, municipal incineration, RoW	kg	1.2E-03	6.3E-04	3.0E-03
Waste carton	treatment of waste paperboard, inert material landfill, RoW	kg	4.8E-04	−2.5E-05	2.4E-04
Waste paper bag	treatment of waste paperboard, municipal incineration, RoW	kg	1.2E-03	6.3E-04	3.0E-03
Waste paper bag	treatment of waste packaging paper, sanitary landfill, GLO	kg	1.2E-03	1.5E-02	2.6E-02
Transportation	market for transport, freight, lorry, unspecified, RoW	kg	7.3E-03	3.1E-03	5.9E-03
Transportation	market for transport, freight train, US	kg	3.3E-03	1.2E-03	2.7E-03
H2O2	market for hydrogen peroxide, without water, in 50% solution state, RoW	tkm	6.7E-02	2.9E-02	6.3E-02
Waste N95 mask	treatment of waste polypropylene, municipal incineration, RoW	kg	1.4E-03	5.3E-02	9.4E-02
Waste N95 mask	treatment of waste polyethylene terephthalate, municipal incineration, RoW	kg	1.4E-03	3.6E-02	6.5E-02
Waste N95 mask	treatment of waste rubber, unspecified, municipal incineration, RoW	kg	1.8E-03	5.5E-02	9.1E-02
Waste N95 mask	treatment of scrap aluminium, municipal incineration, RoW	kg	1.4E-03	2.4E-04	7.7E-04
Waste N95 mask	treatment of scrap steel, municipal incineration, RoW	kg	1.1E-03	4.6E-04	2.6E-02
Waste N95 mask	treatment of waste polyurethane, municipal incineration, RoW	kg	5.4E-03	4.8E-02	8.4E-02
N95 mask	market for textile, non woven polypropylene, GLO	kg	2.5E-01	5.3E-02	1.1E-01
N95 mask	market for textile, non woven polyester, GLO	kg	3.5E-01	1.2E-01	2.3E-01
N95 mask	market for synthetic rubber, GLO	kg	2.4E-01	6.1E-02	1.2E-01
N95 mask	market for aluminium, primary, ingot, RoW	kg	6.4E-01	4.1E-01	9.8E-01
N95 mask	market for sheet rolling, aluminium, GLO	kg	2.4E-02	1.2E-02	2.8E-02
N95 mask	market for metal working, average for aluminium product manufacturing, GLO	kg	1.3E-01	7.9E-02	1.8E-01
N95 mask	market for steel, low-alloyed, hot rolled, GLO	kg	3.7E-01	3.1E-02	7.7E-02
N95 mask	market for sheet rolling, steel, GLO	kg	6.1E-02	7.5E-03	1.7E-02
N95 mask	market for metal working, average for steel product manufacturing, GLO	kg	1.4E-01	3.9E-02	8.2E-02
N95 mask	market for polyurethane, flexible foam, RoW	kWh	2.7E-01	9.5E-02	2.2E-01
N95 mask	market for acrylic binder, without water, in 34% solution state, RoW	kWh	1.2E-01	3.4E-02	7.2E-02
N95 mask	market for printing ink, offset, without solvent, in 47.5% solution state, RoW	kWh	1.8E-01	4.6E-01	1.6E-01
Electricity	market for electricity, low voltage, US-NPCC	kWh	1.2E-02	6.2E-03	8.2E-03
Electricity	market for electricity, low voltage, US-WECC	kWh	1.6E-02	8.3E-03	2.3E-02
Electricity	market for electricity, low voltage, US-TRE	kWh	2.2E-02	1.0E-02	3.6E-02
Electricity	market for electricity, low voltage, US-SERC	kWh	2.3E-02	1.3E-02	2.9E-02
Electricity	market for electricity, low voltage, US-RFC	kWh	2.1E-02	1.2E-02	2.6E-02
Electricity	market for electricity, low voltage, US-MRO	kWh	2.3E-02	1.3E-02	5.0E-02
Electricity	market for electricity, low voltage, US-HICC	Electricity	3.3E-02	1.7E-02	4.7E-02
Electricity	market for electricity, low voltage, US-FRCC	Electricity	2.2E-02	1.1E-02	1.7E-02
Electricity	market for electricity, low voltage, US-ASCC	Electricity	2.3E-02	1.1E-02	2.9E-02
Electricity	SPP[67]	Electricity	2.3E-02	1.3E-02	4.7E-02

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